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FOREWORD

Robotics technology, a technology expected to free man for hazardous to and extreme work environments, as well as increase productivity and improve the welfare of workers, is currently the focus of attention. And the further development and expansion of robotics technology is an immediate task to be shared by the global community.

In this regard, we are delighted to announce the forthcoming 15th International Symposium on Industrial Robots (15th ISIR), the world's most authoritative conference on and with the longest history in industrial robots, in Tokyo.

This will be the fourth time the ISIR has been convened in Japan. The 15th Symposium, supported by the National Coordinators as well as individuals and organizations of various countries, is a gathering of the highest standards in terms of the quality of studeis presented and range of fields covered, and it shall play an extremely important role in determining the future directions for the development and expansion of the industrial robots throughout the world.

In the 15th ISIR, leading experts from various countries will come together to present the results of their indepth studies and express their opinions on a broad range of concepts. The topics shall include:

1. Research and development of industrial robots
2. New application technologies for industrial robots
3. Economic and social evaluation of industrial robots
4. Labor safety and industrial robots
5. Industrial robots and education

The Age of Automation beginning in 1950, is transforming itself into the Age of FMS (flexible manufacturing system) or the Age of Factory Automation. This is the beginning of the age of new, multifunctional automation, and the world holds great expectations regarding the major role to be played by industrial robots in this new era.

Against this background, the convening of the Symposium at this very moment, during which 130 papers from more than 20 countries of the world will be presented on the topics described in the above, withactive discussions by the participants, shall certainly have a great significant impact on the establishment of a new perspective for the industrial robots towards the 21st century.

Finally, we would like to express our gratitude to the National Coordinators, session chairpersons, speakers and the other organizations concerned for their efforts and cooperation in making the 15th ISIR Symposium possible.

Ichiro Kato
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Chairman of the Committee of
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MEASURING/GRINDING SYSTEM FOR WATER TURBINE RUNNER

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ABSTRACT

Measurement work and grinding work involved in manufacturing processes of the water turbine runner are at present hand work except for the machining of circumferences because of complicated 3-dimensional curvatures of the cast runner. The present system is aimed at mechanizing and automating these work. Main components has been developed, and feasibility confirmation and improvement of the system are under way. The system consists of a new-type of multi-joints robot arm, 3-dimensional optical measuring instrument, grinding device with a bracing mechanism, mini-computer, host computer for calculating the robot path, and other components. Main themes of this paper include 1) the description on the overall configuration of the system, and 2) the introduction of the newly developed 6-degree of freedom robot arm with 6 joints including an oblique swivel joint which is accessible to the inside of narrow passages of the pump turbine runner.

INTRODUCTION

Water turbine runners, efficiently converts the potential energy of the water to the rotating kinetic energy, being a key component to the hydraulic power generation. Configuration of the runner as shown in Fig. 1 is determined depending on the generator capacity and the water head. A pump turbine runner for a 300 MW class generator, for example, has an outer diameter of approximately 6 meters, a height at the passage inlet of approximately 0.9 meters and an involvement angle of vanes of approximately 150 degrees when the head is as low as 250 meters, while it has an outer diameters of approximately 5 meters, a height at the passage inlet of approximately 0.3 meters and an involvement angle of vanes of approximately 200 degrees for a high head of approximately 600 meters. Further, the passage of the runner has a complexed three-dimensional configuration consists vanes · crown and band so that the energy can be converted efficiently. The runner equipped with such passages arranged along the circumference is usually made as an integrated body of the cast steel. To manufacture such a runner, some parts of the inlet and outlet are generally turning-machined, but surfaces along the passages that are the most important areas are generally finished by hand. However, finish work as shown in Fig. 1 usually involves, as usual grinding work does, problems of dust, noises, and vibrations. Furthermore, as suggested by the abovementioned runner configuration, the heigher the head is, the lower the height of the inlet of the runner, sometimes making difficult for a person to enter the inside of the runner. Thus mechanization and automation of the finish work for the runner has been strongly desired. In view of such situations, we started the development of a

measuring/grinding system for water turbine runner aimed at mechanizing and automating the finish work of the runner. This paper reports the overall system configuration, especially the construction of the robot arm as a key component, and test and investigation results of the prototype.

1. Necessary Conditions for the System

To study how to realize mechanization and automation of such a measuring/grinding system of the water turbine runner, principal requirements were summed up as follows as necessary conditions.

The system must:

1) Measure accurately the configuration of the solid runner body of cast steel with irregular shapes and excess thicknesses.
2) Be able to process a great many measurement data of 3-dimensional coordinates, compare them with the design values, and give grinding information to minimize the total finish allowances.
3) Be provided with a calculation system and grinding capability to finish intended surfaces following the grinding information of 2).
4) Have a support mechanism which enables measurement and grinding, and flexible traveling in the runner.
5) Be provided with fully automated mechanisms such as an automatic grinding wheel change system.

2. System Configuration

Keeping in mind the above conditions, we examined possible overall system configurations and constructions of each component from different points of view, and with an extra condition of high feasibility, reduced the configurations to a practical system.

2.1 Principal Components The system consists of the following which are also shown in Fig. 2.

1) Host computer as a kernel for controlling data processing and calculation
2) Mini-computer for controlling the entire system
3) A group of servo-controllers
4) 3 robot arms respectively in charge of inlet area, middle area, and outlet area of the runner passage
5) A traveling table and turn table to adjust relative position of the runner and a robot arm
6) Measuring instrument mounted at the arm tip to determine the shape of the runner
7) Grinding device mounted at the arm tip and its support mechanism to finish surfaces of free curvatures
8) Automatic change systems such as one for exchanging an measuring instrument and the grinding device and one for replacing the grinding wheel.

2.2 Basic Features of Each Principal Component Principal components mentioned above (section 2.1) have the following features.

1) The host computer, ACOS-850 (MIPS-15, with 16 MB memories), which delivers control data to the mini-computer.
2) The mini-computer, TOSBAC7/20E (MIPS-0.1, with 768 KB memories), which coordinates controllers. It also can do on-line processing as well as off-line processing between the mini-computer and the host computer.

3) Controllers which consist of a 16 bit microcomputer and an AC servo-driver for controlling a robot arm, measuring instrument, and grinding device.
4) The multi-joint robot arm will be explained in chapter 3.
5) The traveling table and turn table. It will be introduced into the system in the future, and no detailed description is given here.
6) A new-type 3-dimensional optical measuring instrument is adopted which is capable of following 3-dimensional curvatures but has no direct contact with the surface so that it can collect accurate measurements of free curvatures continuously. The measuring principle is based on the triangulation. The instrument is composed three mechanical sections; one of them is the datum axis for optically measuring the distance (R) from the arm center axis to a surface of the work, and the others are the to-and-fro axis (z) for mechanically forwarding streight the optical datum axis and the swivel axis (θ) for turning the optical datum axis. These mechanisms are combined to define a measured curvature with reference to a cylindrical coordinate system R (θ, z), achieving a compact size instrument.
7) The grinding device consists of a grinding section having multi-degree of freedom and a bracing section, which work cooperatively to finish a surface of free curvatures to an intended shape continuously. The grinding section is composed of a 4-degree of freedom arm at whose tip a compact-size, high-power grinder with a grinding wheel (replacable with different types of wheels) is mounted. The bracing section uses a connected differential mechanism which was reported at the previous ICAR (See reference 3.). This mechanism is useful to accommodate load variation depending on the reaction of the grinder and the orientation of the device. The developed grinding device has a compact size.
8) As to the automatic change system, its introduction is expected in the future, and no further description is given here.

2.3 <u>Operation and Control</u> To finish surfaces of a runner to an optimum shape, the runner body must in advance be checked for irregular shapes and excess thickness. Therefore, the traveling route of the robot arm and controlling algorithm of the joint are first established by the host computer, based on CAD data on the runner, construction and data of configurations of the robot arm. Next, a measuring instrument is attached to the tip of the robot arm, which then advances up to a measuring position according to data from the mini-computer, where successive measurement is executed of the runner with in the motion range of the measuring instrument. Then, the arm moves to the next measuring position, and the same measuring procedure is repeated, thus covering all the passage surfaces of the runner. Based on obtained data and CAD data, the host computer determines the finishing strategy for the runner which minimizes working allowance. The computer further works out strategy for grinding directions over finishing surfaces and grinding amount. Based on these data combined with the information of the robot arm configuration, the grinding route and joint control data are derived. Finally, a grinding device is attached to the tip of the arm, which is then brought to the grinding position by the command of the mini-computer, and the bracing section affixes the robot arm taking advantage of the passage wall of the runner. There, the grinding device grinds the surface to the calculated depth within its motions range. Then, the robot arm moves to the next grinding area, and the same procedure is repeated automatically before the arm goes to another grinding area, thus finishing the entire surface of the passages of the runner. These measuring process and grinding process are alternately carried out at a preset cycle to finish the runner to an intended shape.

3. Robot Arm

To meet the abovementioned requirements, robot arms as an key component of the robot must fulfill the following.

1) The robot arm must be able to move around in a runner to which a person is not accessible because of narrow passage or a wide involvement angle of vanes.
2) The robot must have a high enough rigity to bear a high load for grinding work.
3) The robot must have a high accuracy positioning capability as a robot for measurement use.

A new oblique swivel robot arm has been developed which meets the above requirements.

3.1 Basic Construction of the Robot Arm The robot arm is based on an oblique swivel mechanism (reference 1), 2)). Quoting these references, outline and possible functions of the mechanism are mentioned from now on. The oblique swivel mechanism consists of a joint capable of swiveling around the oblique axis (abbreviated as Jo Gear in after) with an oblique angle of α (designated as an oblique swivel angle) as shown in Fig. 3 (a), and a concentric rotational joint as shown in Fig. 3 (b) (abbreviated as Jc), both of which are alternately connected as shown in Fig. 4. This oblique swivel robot arm has been adopted for the sake of the following merits.

1) If the oblique swivel joint Jo has an oblique angle α within about 30°, its design is as good as that of the concentric rotational joint as shown in Fig. 3, with a strong, compact and light-weight construction.
2) The construction of articulated short cylinders gives an smooth external appearance, and has no directional nature, capable of taking various postures and workable inside narrow environments.
3) Shell construction of the oblique swivel mechanism in itself has a high rigidity. The shell construction provides a hollow core along the center of the arm, where, power and control cables leading to different joints can be laid. Protection of these cables and measures against dust is easy to take because of the shell construction, providing a high environment-proof characteristics during grinding work.
4) The maximum torque which the actuator of the oblique swivel joint must generate is small as compared with conventional vertical swivel joints (abbreviated as Jv hereinafter). As a result, the power output of the mechanism can be increased, and more compact and light weight design is possible.

Detailing a little more above item 4); take an example as shown in Fig. 5 in which the oblique swivel mechanism swings its arm tip in a sagittal plane, and suppose that the point * in the figure has a moment M* if the point is a vertical swivel joint Jiv. If this point is replaced with an oblique swivel joint Jio (with an oblique angle of α), and the vertical swing motion is done by this joint in cooperation with adjacent concentric rotational joints Jic and Ji + lc, joint Jio would have at most a torque of $M^*\sin\alpha$, a half that to be generated by the vertical swivel joint when α is 30°. Although this is not always true, an oblique swivel joint would be serviceable enough in such a case as studied in the present project, that is, in such application of a robot arm as in narrow, long and curved passage in a water turbine runner.

3.2 Trial Manufacture of a Robot Arm and Operation Test A robot arm model for a water turbine runner was manufactured for feasibility study. This robot arm had abovementioned basic construction with some improved features for practical use. The outline view of the robot arm is shown in Fig. 6 (a), (b). The arm is composed of slender arms with 6 axes, that is, a front-to-rear axis (J_1L) as the foot, 2 oblique swivel joints (J_1o, J_2o) and 3 concentric rotational joints (J_1c, J_2c, J_3c) which are combined alternately. For design of this robot arm, the number, spacing, oblique angle α and external dimensions were first determined based on the drawing of the model runner. Next, simplified mini-models of the robot arm and the runner were fabricated to confirm basic functions. Finally, taking advantage of the computer simulation, details were investigated to establish final constructions, dimensions and shapes. Fig. 7 shows typical example of the joint construction of the robot arm. This joint construction has following advantages as well as already mentioned merits.

1) The built-in driver composed of combined approx. 70W actuator and improved harmonic drive speed reducer with a 1/250 reduction ratio allows a compact size, a high torque output and capability to handle a large load.
2) The frame is mostly constructed of aluminum alloys, which, together with the thin-wall, large diameter, high load capacity ball bearing for the joint bearing, achieves a robot arm of light weight, high rigidity construction.
3) The flange-connector type unit between joints allows more easy assembly and disassembly work.
4) A speed detector (T/G) is connected to the motor via an over-drive gear (provided with an anti-backlash mechanism), to increase a feed-back amount of speed, enhancing stability of the control system at low speeds.
5) A position detector (Re) equipped between a fixed part of the joint and the output axis via an over-drive gear (provided with an anti-backlash mechanism) to compensate for elasticity and backlash in the bearing as well as increase feed-back amount of positions, realizing high-accuracy positioning.

Typical specifications and performances of the robot arm include: a joint length of approx. 200 mm, an outer diameter of approx. 200 mm, a joint weight of approx. 25 kg, an oblique angle α of the joint of 15°, an output torque of 30 kg-m, and a positional reproducibility of approx. $\pm 0.01°$.

As a result of an operation test, a robot arm of the abovementioned construction could support a load of approx. 30 kg at the tip of an arm approx. 2.5m long, and place the load at a predetermined position with an absolute positional accuracy of within ± 5 mm and reproducibility of ± 0.5 mm or less, and the arm could enter smoothly along the passage taking time of approx. 80 seconds. Thus it has been made clear that the robot arm with oblique swivel joints is serviceable enough for such application as the water turbine runner which has narrow, long and bent passages.

4. Afterwords

This paper has reported first the overall system construction of the robot system including principal components, construction of each component, and operation and control of these components, referring to necessary conditions for the system as a measuring/grinding system for the water turbine runner. Next, functions and basic construction of the robot arm as the key component of the system were detailed. Finally, test results of the prototype arm were reported which prove that the

robot system is applicable to actual finish work. Development of principal components of the present robot system has completed, and is now entering the stage of the system validity confirmation and application test. Further improvement in functions will be made until completion of the system when increased accuracy and amount of data as well as automated work will bring some labor saving in the measuring work and also labor saving equivalent to some persons in the grinding work as well as improved workability.

5. Acknowledgement

We are deeply appreciative of the persons concerned of Tokyo Institute of Technology and Toshiba Corporation who cooperated for developing the measuring/grinding system for the water turbine runner.

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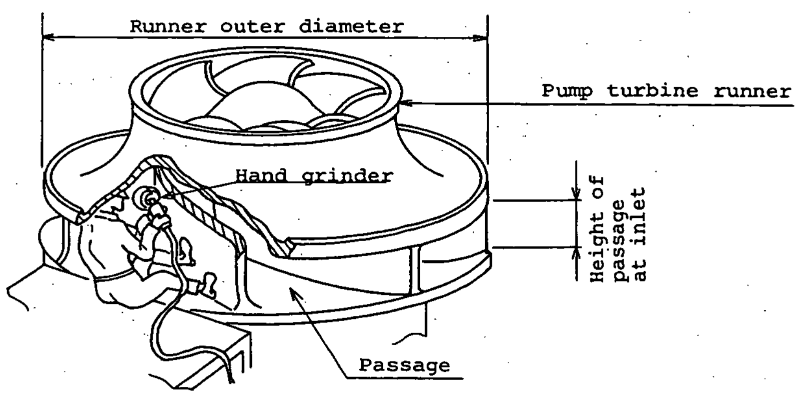
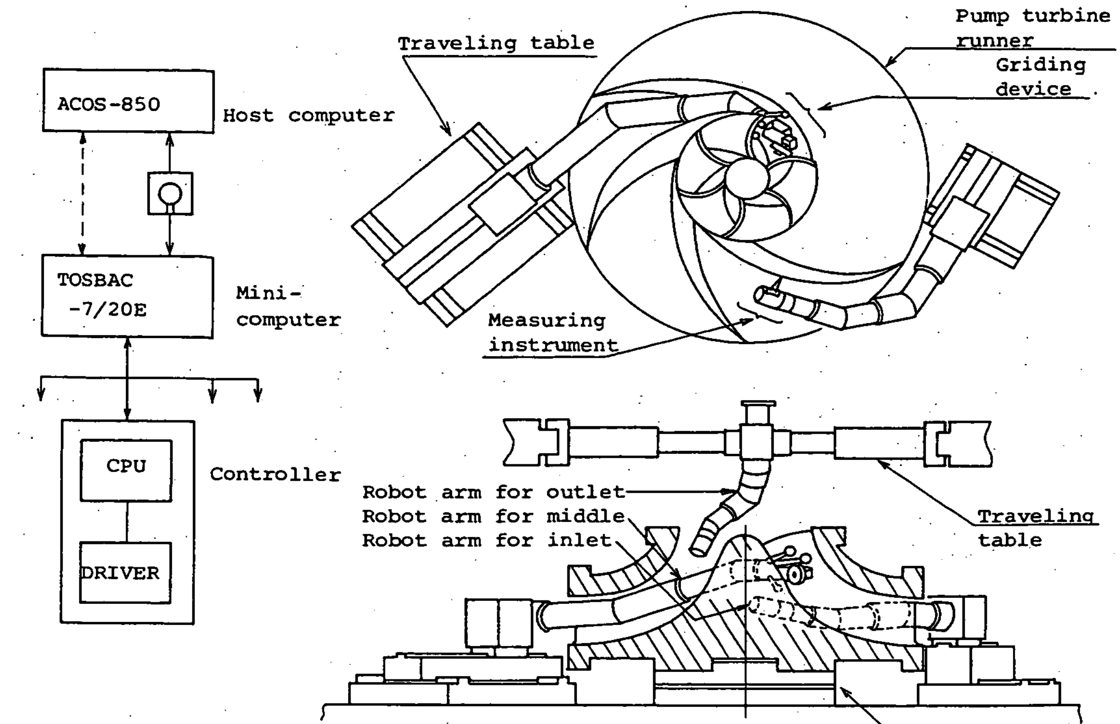
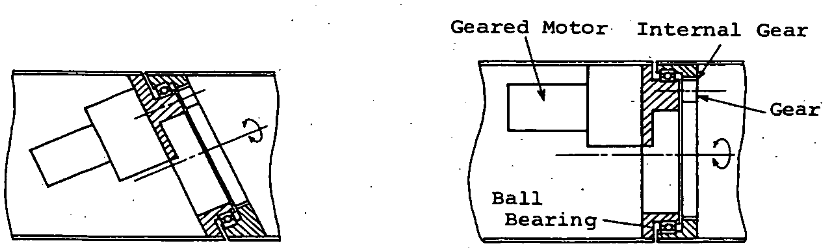


Fig. 1 An Example of Manual Finish Work



(a) Control system (b) Robot arm arrangement

Fig. 2 Outline of System Configuration



(a) oblique swivel joint (b) concentric rotational joint

Fig. 3 Design example of the joint mechanism for oblique swivel mechanism

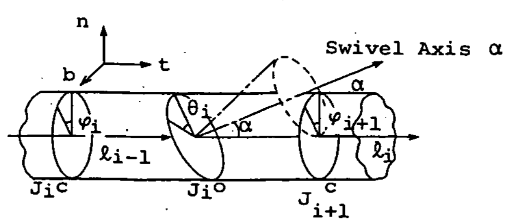


Fig. 4 Oblique swivel mechanism and its nomenclature

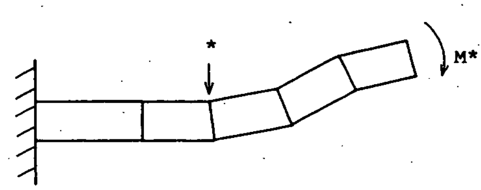
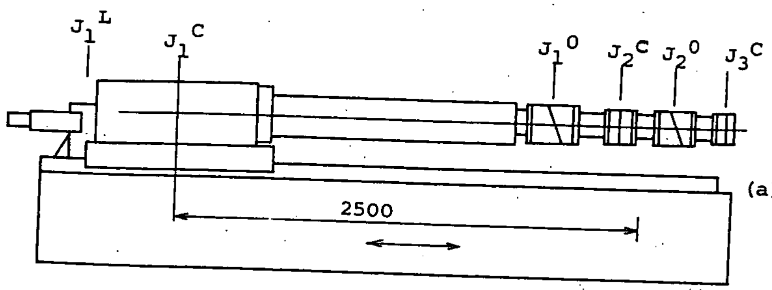
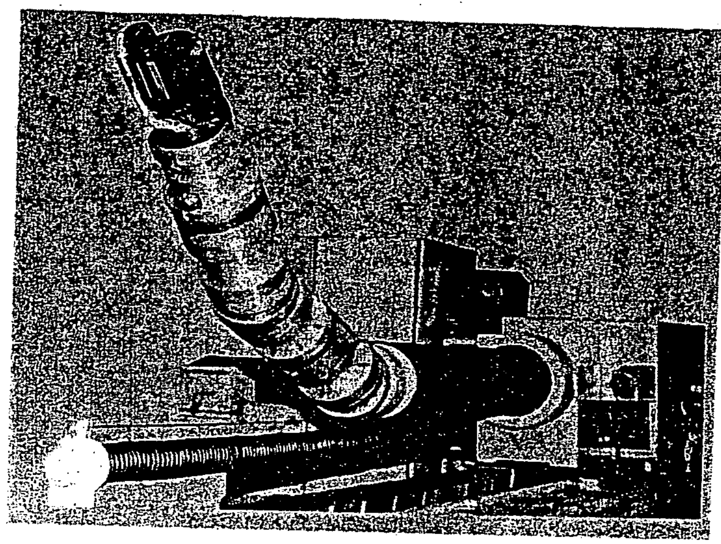


Fig. 5 The motion of oblique swivel mechanism



(a) Construction axis



(b) Example of Working robot arm

Fig. 6 Prototype Robot Arm

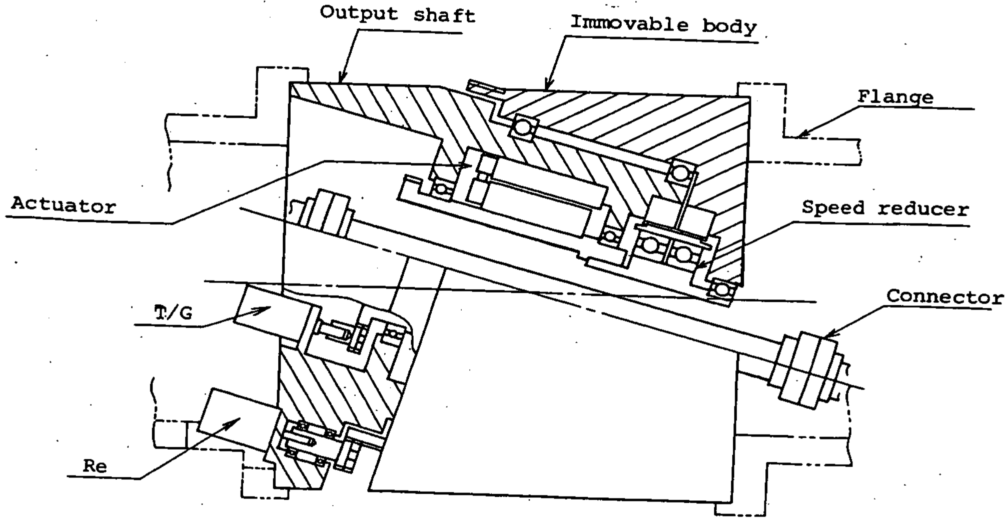


Fig. 7 Prototype oblique swivel joint